Sensitivity of Nb_3Sn Rutherford-type Cables to Transverse Pressure

E. Barzi, T. Wokas, A. V. Zlobin

***Abstract*— Fermilab is developing high field superconducting magnets for future accelerators based on Nb_3Sn strands. Testing the critical current of superconducting cables under compression is a means to appraise the performance of the produced magnet. However, these cable tests are expensive and labor-intensive. A fixture to assess the superconducting performance of a Nb_3Sn strand within a reacted and impregnated cable under pressure was designed and built at Fermilab. Several Rutherford-type cables were fabricated at Fermilab and at LBNL using multifilamentary Nb_3Sn strands. The sensitivity of Nb_3Sn to transverse pressure was measured for a number of Nb_3Sn technologies (Modified Jelly Roll, Powder-in-Tube, Internal Tin, and Restack Rod Process). Results on the effect of a stainless steel core in the cable are also shown.**

***Index Terms*—Rutherford cable, Nb_3Sn, transverse pressure, critical current.**

I. Introduction

THE critical current, I_c, of a Nb_3Sn virgin strand is reduced during magnet fabrication and operation. In addition to cabling, cable compression in the coil due to precompression, cool-down and Lorenz force decrease the original I_c. This is due to J_c sensitivity of Nb_3Sn to strain. Previous work on transverse stress effect in earlier Nb_3Sn materials includes [1]-[3]. The device herein described allows providing quantitative information on the I_c degradation occurring under stress in a Nb_3Sn superconducting (SC) magnet in a very inexpensive way, i.e. with strand tests as opposed to cable tests, and by using the existent Short Sample Test Facility (SSTF) at Fermilab. This is as much more convenient as recent I_c data obtained in cable tests have shown an excellent correlation with strand measurements [4].

To reproduce the real conditions in which the superconductor will operate in the magnet, the pressure is applied to the strand within a Rutherford cable. To prevent current sharing, the housing cable is made of Cu. An impregnation fixture that is used also for reaction was designed. The cable sample is stacked with a Cu cable, and the two are reacted and impregnated together to improve pressure distribution during testing.

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II. Experimental Procedure

A. Test Device

The test device is shown in Fig. 1 and a more detailed description can be found in [5]. The cable sample (1) is compressed between two Inconel plates. The bottom plate (2), made of two spherically coupled parts, is driven up by an Inconel rod assembly (3), which is pulled up by a 20 ton hydraulic cylinder placed on a stainless steel support on the top flange of the device. The top plate (4) is welded to an Inconel tube (5), which is itself welded to the top flange. The assembly is immersed in boiling He at 4.2 K within the 64 mm bore of a superconducting solenoid. The device was designed such as to center the cable sample within the solenoid. The copper leads were designed to carry currents of up to 2000 A. After reaction and impregnation, the cable sample is carefully mounted at the bottom of the device by soldering the ends of a strand to the current leads. The strand ends are long enough to ensure current transfer. To allow for the differential thermal contraction between copper and Inconel, the current leads are free to move vertically within a bellows at the top of the device. To decouple the rod motion from the current leads, another smaller bellows is used.

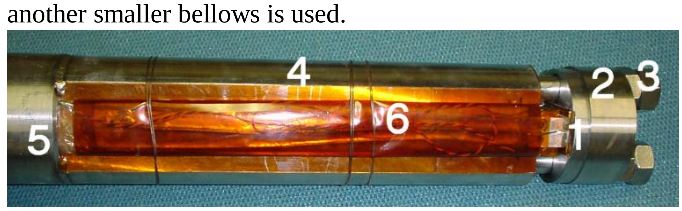

Fig. 1. Test device.

Fig. 2. Reaction/impregnation fixture after impregnation and removal of the side plates.

B. Sample Preparation

To prevent current sharing, cable samples were prepared by extracting a strand from a piece of SC Rutherford cable and inserting it in place of a Cu strand within a shorter piece of cable 14.24 mm wide and 1.8 mm thick, made of Cu strands. A Cu cable with SS core is used to study its effect on pressure sensitivity. One edge of the extracted strand is placed in the middle of the housing cable. The ends of the selected strand are 20 cm to ensure current transfer once soldered to the current leads. A single fixture was designed for both reaction and impregnation in order to limit handling of the sample after reaction. This fixture, opened, is shown in Fig. 2. After reaction in argon atmosphere, the sample is delicately removed from the fixture in order to spray the latter with mold release. The sample is carefully replaced in the fixture, and two small copper plates are soldered to the strand to reinforce the bends. The fixture is then closed for impregnation with CTD epoxy.

C. Measurement Procedure

After applying very slowly the desired load by means of a Power Team hydraulic cylinder supplied by an Enerpack pump, the voltage-current (VI) characteristics were measured in boiling He at 4.2 K, in a transverse magnetic field, B, between 10 and 14 T. The voltage was measured at the ends of the cable sample by voltage taps placed 53 mm apart, just outside the cable length. The sample critical current I_c was determined from the VI curve using the backward extrapolation criterion. An additional pair of voltage taps was placed on the strand tails to ensure sample protection. To counteract the lateral Lorentz force generated by the relative directions of magnetic field and transport current, two thin G10 wings were placed at the sides of the sample through holes around the bottom rods. The estimated uncertainty of the I_c measurements in this study is within ±5%. Tests were carried out at pressures up to 200 MPa.

TABLE I
PARAMETERS OF TESTED CABLE SAMPLES

Powder-in-Tube					Modified Jelly Roll					Internal Tin			Restack Rod Process		
Billet No	HT No	PF, %	Fabricated w/core	Tested w/core	Billet No	HT No	PF, %	Fabricated w/core	Tested w/core	PF, %	Fabricated w/core	Tested w/core	PF, %	Fabricated w/core	Tested w/core
151	A	85.6	Y	N	113	D	87.3	N	N	88.6	N	N	88.5	N	N
151	B	89.5	Y	Y	113	D	88.5	N	N	89.5	Y	N			
151	B	91.5	Y	Y	187	D	86.6	Y	N	89.5	Y	Y			
159	C	86.7	N	N	187	E	88.4	Y	Y						
159	C	88.6	N	N											
181	C	89.5	N	Y											

TABLE II
PARAMETERS OF THE STRANDS USED IN THE CABLE S

Strand Parameter	PIT 151	PIT 159	PIT 181	MJR 113	MJR 187	IT (ITER-type)	RRP
Strand diameter, mm	1.000	1.000	1.000	1.000	1.000	1.000	0.700
I_c(12T), A	~ 620	~ 720	~ 780	~ 700	~ 900	~ 200	> 500
d_{eff}, μm	~ 50	~ 50	~ 50	~ 110	~ 110	~ 5	~ 80
Cu, %	48.7	54.8	53.6	47.8	46.7	58.7	50.0
Twist pitch, mm/turn	20	20	20	23	23	13	12

TABLE III
HEAT TREATMENT CYCLES

Heat Treatment			Step 1	Step 2	Step 3
A	PIT	Ramp rate, ^oC/h	25		
		Temperature, ^oC	700		
		Duration, h	60		
B	PIT	Ramp rate, ^oC/h	25		
		Temperature, ^oC	655		
		Duration, h	170		
C	PIT	Ramp rate, ^oC/h	25	50	75
		Temperature, ^oC	210	340	675
		Duration, h	168	40	65
D	MJR, IT	Ramp rate, ^oC/h	25	50	75
		Temperature, ^oC	210	340	700
		Duration, h	48	48	40
E	MJR, RRP	Ramp rate, ^oC/h	25	50	75
		Temperature, ^oC	210	340	650
		Duration, h	100	48	72

D. Strand and Cable Description

The parameters of the samples that were tested are shown in Table I. For completeness are included data from [6]. The PIT, MJR 113 and IT cables were fabricated at FNAL, whereas the MJR 187 and RRP cables were fabricated at LBNL. All cables but the RRP's are 28-strand keystoned with the same pitch length of about 110 mm, corresponding to a transposition angle of 14.5±0.1 degrees. The packing factor was varied by modifying the cable mean thickness, whereas cable width and keystone angle were kept within 14.24±0.025 mm and 0.91±0.1 degrees respectively. The RRP cables are 39-strand rectangular and keystoned with a pitch length of 111 mm, corresponding to the same transposition angle of 14.5±0.1 degree. For the keystoned cables, the keystone angle was 0.96±0.1 degrees. The SS core material is 9.52 mm by 0.025 mm, 316-L annealed. Two different multifilamentary Modified Jelly Roll (MJR) Nb_3Sn strands and a Restack Rod Process (RRP) strand by Oxford Superconducting Technology (OST), three Powder-in-Tube (PIT) strands by ShapeMetal Innovation (SMI), and an IT of ITER-type design by Intermagnetics General Corporation (IGC) were used to manufacture the cables. These strands parameters are shown in Table II, and the heat treatment cycles used in Table III.

III. Results and Discussion

A. IT Samples

Fig. 3 shows I_c as a function of transverse pressure at 12 T for the IT samples. The lines on the plot indicate load sequences. For instance, in the case in Figure, the load sequence for the IT 88.6% sample started at 27.9 MPa to 83.6, to 139.4, back to 27.9, to 147.8, back to 27.9, to 156.1, back to 27.9, to 167.3, back to 27.9, to 175.6, back to 27.9, to 175.6, back to 27.9, to 184, back to 27.9, to 195.2, back to 27.9, and to 195.2 MPa. This is typically done to pinpoint the minimum pressure at which irreversibility starts occurring. From these data it appears that in the case of IT cables without and without a core, I_c degradation at 12 T is negligible and reversible up to about 140 MPa of pressure. Irreversibility begins at pressures somewhat larger than this value, with a 5% residual degradation at about 150 MPa. However, at about 200 MPa of pressure, samples without a core show an I_c degradation of 70 to 80% at 12 T, most of which is maintained all along the unloading cycle down to 27.8 MPa. One can notice though that past 140 MPa of pressure, the sample with core appears to degrade at half the rate of the samples without core. More statistics is needed to confirm this behavior is systematic. The results obtained on the IT samples could be compared with actual cable tests performed on 41-strand cables made of 0.7 mm IT strands and featuring a core [4]. This was done by plotting the I_c normalized to that obtained at the lowest pressure, as shown in Fig. 4. One can notice a better consistency of the results at comparable fields in the case of samples with a core, as expected.

B. MJR Samples

Fig. 5 shows the critical currents normalized to those at minimum loads as a function of transverse pressure at 12 T for the MJR samples. As the first sample that was tested (lozenges) was loaded using large pressure steps, that did not allow accurate location of the onset of irreversibility (somewhere between 80 and 140 MPa), when testing the second sample (triangles), load steps were reduced in size. In this case the onset of irreversibility was found to be at around 140 MPa, and in any case below 150 MPa. After loading up to about 210 MPa, I_c degradation was on the order of 80%. Although these two samples showed an excellent reproducibility, the third sample that was tested behaved somewhat differently, showing a degradation of about 20% already at around 110 MPa. Past this value, the degradation rate was about the same as for the other samples. Again, more statistics are needed to understand if these differences are real.

C. PIT Samples

The normalized results at 12 T for the PIT samples are shown in Fig. 6. In the case of the samples without core, up to about 60 MPa of pressure the I_c degradation was found to be reversible for at least one sample, and smaller than 15% for all samples. The onset of irreversibility occurred beyond 60 MPa. However, at 100 MPa the I_c degradation was already about 20% or larger for some samples, and appeared to rapidly increase at larger loads. After loading up to about 200 MPa, the I_c degradation was on the order of 90%, all of it permanent. However, whereas the best of the PIT samples without core featured 10% degradation already at 100 MPa, most of the samples with core showed a similar degradation at a load as large as 140 MPa. The only sample with core, PIT 181, that had a faster degradation rate at the beginning, eventually met the curve of PIT 151 89.5% with core at about 150 MPa with 30% degradation only, and then resumed the same degradation rate.

More data are needed to understand whether the spread observed in the results of these PIT cables are due to a few damaged samples or indicates a real physics phenomenon. This latter conclusion would be consistent with the variation observed in short sample limits of PIT coils made and tested at Fermilab [7].

D. RRP Samples

Until more statistics is gathered, caution is needed in interpreting Fig. 7 that shows results at 12 and 14 T of the only RRP sample that was tested. It seems that the degradation rate at 14 T is 4 to 6% larger than at 12 T, but yet this is comparable with the measurement uncertainty.

IV. Conclusion

These results obtained on sensitivity of Nb_3Sn to transverse pressure already show solid consistency, as evidenced in Fig. 8, where the normalized I_c is plotted as a function of transverse pressure for all samples at 12 T. It is using these data to take into account I_c degradation due to the loads that short sample limit ranges for the PIT coils made at Fermilab could be appropriately and correctly calculated. The data obtained so far seem to indicate that a SS core helps reducing sensitivity to transverse pressure in Nb_3Sn Rutherford cables. This has yet to be theoretically understood, and more data are needed to refine the present findings.

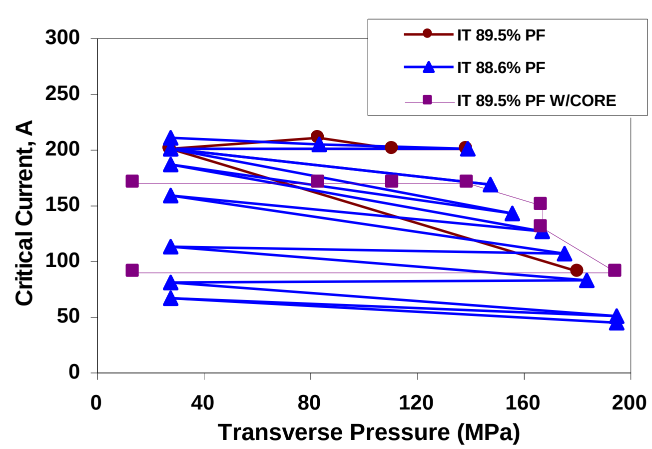

Fig. 3. I_c vs. transverse pressure for the IT samples at 12 T.

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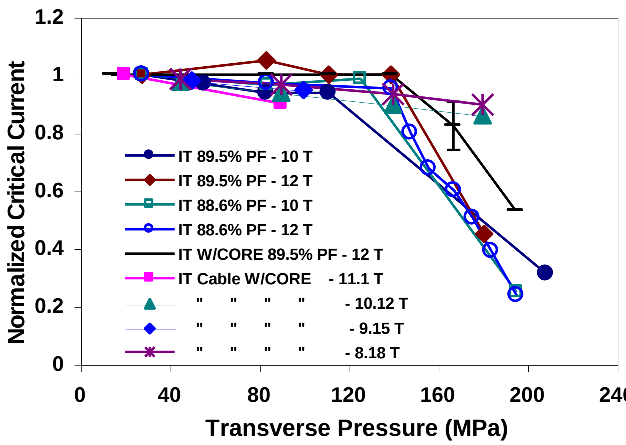

Fig. 4. Normalized I_c vs. transverse pressure for the IT samples and comparison with results obtained on actual cable tests [4].

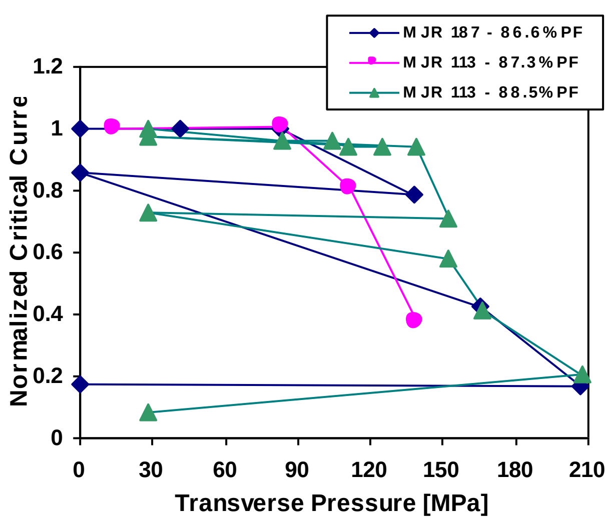

Fig. 5. Normalized I_c vs. transverse pressure for the MJR samples at 12 T.

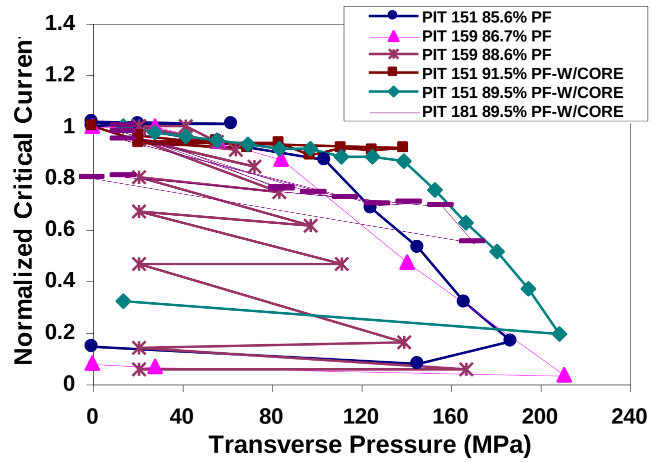

Fig. 6. Normalized I_c vs. transverse pressure for the six PIT samples at 12 T.

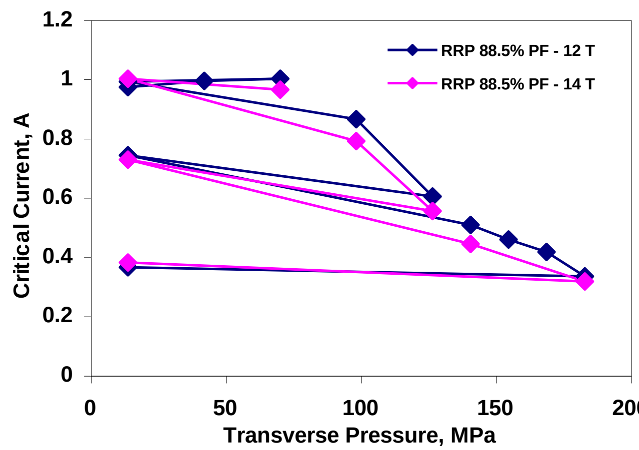

Fig. 7. Normalized I_c vs. transverse pressure for the RRP sample at 12 and 14 T.

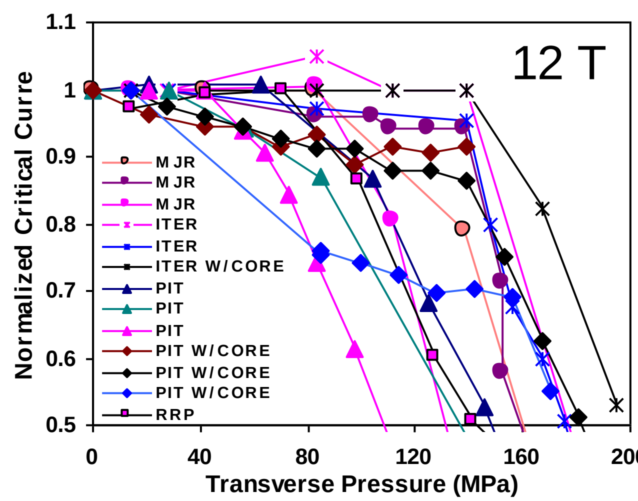

Fig. 8. Normalized I_c vs. transverse pressure for all samples tested at 12 T.